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13. ABSTRACT (Maximum 200 words)

Analysis and modeling of boundary layer influences on atmospheric cold fronts are carried out with data sets obtained from two field programs. These programs are the STorm-scale Operational and Research Meteorology Fronts Experiment Systems Test (STORM-FEST), February–March 1992, and the MICROFRONTS experiment, March 1995. Particular emphasis is placed on the analysis of data to explore the role of the boundary layer on frontogenesis and on the development of turbulent bursts that characterize the stable nighttime boundary layer. These investigations are used to develop theoretical models which are able to isolate the principal physical processes that can explain the observations obtained. The MICROFRONTS data set contains high-frequency data obtained by both one and two hot-wire anemometers situated at the 3 meter level. These data are being analyzed to establish the relative importance of kinetic energy dissipation and turbulent transfers in events occurring in the planetary boundary layer. This work will be used to provide improvements to surface layer parameterizations of turbulent dissipation, which is poorly represented in mesoscale models, particularly under nonstationary conditions.

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Final Technical Report

Front Boundary - Layer Processes

15 January 1995–14 January 1998

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1. Introduction

Front boundary-layer processes, grant no. F49620-95-1-0141, is principally directed to the analysis and modelling of observational data collected during two field campaigns:

1) The STorm-scale Operational and Research Meteorology-Fronts Experiment and Systems Test (STORM-FEST), conducted in the Great Plains, 1 February–13 March 1992, and

2) The MICROFRONTS Experiment, conducted in DeGraff, Kansas, 1–30 March 1995.

STORM-FEST was organized with the U.S. Weather Research Program, and the P.I. participated in this six-week program with one research associate and two graduate students. The principal aim of this observational program was to focus on mesoscale aspects of atmospheric fronts in the Great Plains of the United States. The principal activity supported under this grant was a detailed observational, numerical and theoretical analyses of the low-level structure of cold fronts, specifically boundary layer influence on fronts. The resources available were sufficient to examine, in detail, mesoscale aspects of two cold fronts that passed through the STORM-FEST array. It, however, became apparent that turbulent energy dissipation in frontal zones could not be examined with the observational network available in STORM-FEST. The highest observational frequency for instruments was 10Hz. this upper limit does not resolve motions in the full Kolmogorov inertial subrange of turbulent energy.

MICROFRONTS was organized to collect data in the turbulent boundary layer, particularly to examine kinetic energy dissipation in prefrontal, frontal transition zone, and in postfrontal regimes. The distinguishing characteristic of the MICROFRONTS field program was the collection of high frequency (9.6 kHz) data from either one or two hot-wire anemometers located at 3 m above the ground. Data were collected during the passage of two cold fronts.

Both field campaigns and the accompanying research were carried out with financial support of the Air Force Office of Scientific Research, and field observing support from the Surface and Sounding Systems Facility (SSSF) of the National Center for Atmospheric Research (NCAR).

2. Accomplishments

a. STORM-FEST

The specific aims are provided in section 1. These goals have been met by a collective effort involving scientists from the University of Colorado (CU), NCAR, UCAR and NOAA, and reported by Miller et al. (1996) and by Blumen et al. (1996). A collaborative effort was required because of the large data sets involved and because of the expertise needed to examine particular data, e.g., radar, aircraft and wind profiler data. The 9 March 1992 frontal event provided an excellent case of cold front propagation through a prefrontal thermodynamically well-mixed boundary layer. The mixing in this case was brought about by surface heating in the prefrontal air, while the cold air was under continuous cloud cover. Many numerical model studies of this type of situation have been undertaken, but this is one of the first studies in which a relatively dense data set is available to document the frontal passage over several hours.

Three predominant scales associated with this front were delineated: 1) a broad, subsynoptic frontal zone ($\approx$ 250–300 km wide) of modest temperature and wind gradients; 2) a narrower mesoscale zone ($\approx$ 15–20 km wide) with much larger gradients; and 3) a zone of near-zero-order discontinuity ($\lesssim$ 1-2 km wide). There was a significant diurnal cycle in the magnitude of the potential temperature gradient across both the sub-synoptic and mesoscale frontal zones, but imposed upon an underlying more gradual increase over the three days.

The theoretical work focussed on providing a quantitative evaluation of the small-scale processes associated with the formation of the 1–2 km wide frontal zone, illustrated by the surface Portable Automated Mesoret (PAM) stations aligned normal to the frontal zone. The principal physical aspects of this frontogenesis are shown to be associated with cross-frontal differential heating, associated with differential cloud cover, and to a lesser extent convergence of warm and cold air toward the front.

The principal value of this investigation is associated with the density and diversity of data available for analysis and for use in verification of model results. Model studies carried out in isolation suffer deficiencies: notably verification often takes place among model results rather than with an observational data set. Furthermore, the model calculations are constrained by grid resolution, lateral diffusion, or some type of smoothing procedure that is explicitly used to maintain stability, and physical parameterizations of subgrid scale processes. These data, and the results obtained in the theory and analysis presented, are expected to be of use to numerical modeling activities that are designed to improve the prediction of fronts and associated weather for many purposes including aircraft operations.

A detailed analysis of the cold front that was observed on 20–21 February 1992 has been presented by Ostdiek and Blumen (1995,1997). The former study provides observational verification of the Hoskins-Bretherton deformation model of frontogenesis. The observed forcing for this frontogenesis event was a synoptic-scale wind deformation field. Both temporal and spatial predictions of the model agree to a large degree with the observed fields above about 1.2 km, which is not unexpected, since the model is based on inviscid dynamics.

Attention was directed to analysis of the low-level structure of the front by Ostdiek and Blumen (1997) and by Blumen (1997). Ostdiek and Blumen showed evidence for inertial oscillations in the vicinity of frontal zones in the layer between 10 meters and approximately 1.2 kilometers using surface and profiler data. The analysis also revealed that the frictional balance in this low-level boundary layer is decoupled from the inertial oscillation dynamics, allowing both processes to exist and evolve separately during the night when the inertial oscillations are more readily observed. Blumen (1997) provided a theoretical analysis that also showed how inertial oscillations could co-exist and be modified by the frontal circulations: the inertial frequency is unaltered, but the amplitude of the oscillation is intimately related to the frontal dynamics. This work is proceeding, and five years of profiler data are being examined to document the relative frequency of inertial oscillations during frontal events that occur in the mid-west. The presence of such oscillations is association with fronts needs to be understood in greater detail, with the aim of modifying existing frontal models that exclude unbalanced motions of this type in the basic dynamical framework.

b. MICROFRONTS

In order to obtain data that encompasses the dissipation range of turbulence, the principal investigator together with N. Gamage (University Corporation for Atmospheric Research) and L. Mahrt (Oregon State University) carried out a limited field campaign (MICROFRONTS) in DeGraff Kansas from 1–30 March 1995. The NCAR ASTER facility (three 10 m towers), a radiosonde facility (CLASS) and hot-wire anemometers were mounted on one ASTER tower at the 3 meter level to obtain 9600 Hz wind data. Radiosonde measurements were taken during frontal events, and the ASTER measurements, restricted to 10 Hz, provided three components of the wind, plus temperature and humidity data. The two year period following the field campaign has largely been spent on acquiring quality controlled data. The radiosonde data were available by the summer of 1995, the ASTER data were available in January 1996 and the hot-wire calibrations have only recently been completed. Figure 1 represents a spectrum of kinetic energy based on a combined sonic anemometer and hot-wire anemometer data set. Over six decades are resolved, ranging from the low-frequency energy containing motions to high frequency dissipative scales.

The analyses of frontal dissipation have used data from the two frontal passages. The first occurred at about 2030 CST on 19 March 1995, and the second occurred at approximately 1300 CST on 26 March 1995. These two frontal events provide a very useful framework for analysis of surface layer turbulence. The Monin-Obukhov length L represents a measure of the relative importance of mechanical and convective turbulence. The variable $\zeta = z/L$, where z is height above the ground, is a quantity that characerizes conditions in the surface layer during stable ($L > 0$) and unstable ($L < 0$) conditions.

In Figure 2, the ζ-trace shows the stable stratification ($\zeta > 0$) in the surface layer before the March 19 front, the neutral stratification ($\zeta \approx 0$) immediately after the front, and the eventual relaxation into stable conditions approximately 2 hours after the front had passed. The bottom trace shows the dissipation measured by the hot-wire anemometer. The ζ-trace in Figure 3 shows the slightly convective conditions ($\zeta \approx -0.03$) in the surface layer before the March 26 front arrives. After the front passed, ζ began to approach zero slowly because of the residual upward temperature flux from the warm surface of the Earth.

A principal difference in the frontal passages, that should bear on the nature of turbulent dissipation within the frontal zones, is the fact that the March 19 front is moving into a statically stable prefrontal environment while in the March 26 case the prefrontal environment is convectively unstable. These differences in the prefrontal environment provide the basic focus of this frontal research on dissipative processes.

The limitation of inertial subrange estimates of dissipation is an important question to be answered, because these approximate methods are often used for parameterization purposes, and their accuracy is an important consideration in mesoscale modeling efforts.

Papers for publication based on observations of frontal dissipation, an examination of the differences observed when the frontal passage occurs during the daytime (convective prefrontal conditions) and nocturnal (very stable prefrontal conditions), and a theoretical development of the role of dissipation in frontal zones are all expected to be submitted within the next 6 months.

The data collected during MICROFRONTS also revealed some interesting observations of the nighttime surface layer. The stable nighttime surface layer under light wind conditions is usually relatively quiescent: both convective and mechanical instabilities and turbulence are suppressed. Yet quiescent periods may be interrupted by turbulent bursts as shown in Figure 4. The source of these bursts is in most cases unknown. There are suggestions that they are produced by breaking Kelvin-Helmholtz billows that exist along an undulating interface that may be sampled intermittently by a fixed sensor. Alternatively, the bursts may represent patches of turbulence, generated elsewhere, that are advected past the sensor in a more or less random manner. This explanation is one that has appeared frequently in the oceanographic literature and to some extent in the atmospheric literature.

Work has recently been initiated to understand the source of these bursts, also observed in other field studies, but are not well understood. Further, such bursts are not described by existing similarity theory, which is used relatively successfully under convective conditions. Consequently, there is a need to provide a basic foundation for these events, and determine their relative importance in modeling boundary layer processes.

This more recent activity will constitute a principal research focus over the next few years, and present results are as yet preliminary. A presentation of characteristics of the nighttime surface letter, based on MICROFRONTS data, is presently under review (Mahrt et al., 1997).

c. Mixed baroclinic-barotropic instability

Frontal models based on instability of a basic shear flow have been successful in understanding the development of frontal circulations and frontogenesis in the atmosphere. The Eady model of baroclinic instability has served as a paradigm for such studies. Blumen and Barcilon (1995, 1997a, b) have extended the model of baroclinic instability by introduction of lateral shear. The dynamics is investigated in the case when 1) barotropic instability does not occur, although baroclinic instability tends to be stabilized by the lateral shear, and when 2) barotropic instability is possible and the system is more unstable than when either baroclinic or barotropic instability occurs in isolation. The mixed baroclinic-barotropic stability problem has made use of a two layer representation of the Eady model and, for the first time, a completely analytical solution of the mixed stability problem is presented and analyzed in detail. This work is continuing, with application to jet-like barotropic flows to be considered.

3. Personnel supported

Principal Investigator: William Blumen, Professor, University of Colorado, Program in Atmospheric and Oceanic Sciences.

Co-Investigator: Nimal Gamage, Research Scientist, Joint Office for Science Support, University Corporation for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307

Mark Piper, Graduate Research Assistant, Program in Atmospheric and Oceanic Sciences, University of Colorado. Supported by AASERT grant F49620-97-1-0448 effective 1 June 1997.

4. Publications

1) Ostdiek, V., and W. Blumen, 1995: Deformation frontogenesis: observation and theory. Journal of the Atmospheric Sciences, 52, 1487–1500.

2) Barcilon, A. and W. Blumen, 1995: The Eady problem with linear horizontal shear. Dynamics of Atmospheres and Oceans, 22, 115–133.

3) Miller, L. J., M. A. LeMone, W. Blumen, N. Gamage, R. J. Zamora, and R. L. Grossman, 1996: The low-level structure and evolution of a dry arctic front over the central United States. Part I: Mesoscale observations. Monthly Weather Review, 124, 1648–1675.

4) Blumen, W., N. Gamage, R. L. Grossman, M. A. LeMone, and L. J. Miller, 1996: The low-level structure and evolution of a dry arctic front over the central United States. Part II: Comparison with Theory. Monthly Weather Review, 124, 1676–1692.

5) Ostdiek, V. and W. Blumen, 1997: A dynamic trio: inertial oscillation, deformation frontogenesis and the Ekman-Taylor boundary layer. J. Atmospheric Sciences, 54, 1490–1502.

6) Blumen, W. 1996: A model of inertial oscillations with deformation Frontogenesis. J. Atmospheric Sciences, 54, 2681–2692.

7) Blumen, W. and A. Barcilon, 1997: Application of Bretherton's interpretation of baroclinic instability in the presence of horizontal shear and compressibility. Dynamics of Atmospheres and Oceans, in press.

8) Mahrt, L., J. Sun, W. Blumen, T. Delany, G. McClean, and S. Oncley, 1997: Nocturnal boundary layer regimes. Boundary Layer Meteorology. Submitted.

9) Ostdiek, V., 1995: Deformation frontogenesis and related boundary layer processes: observation and theory. Ph.D. thesis, University of Colorado, 164pp.

This Ph.D. thesis (Ostdiek, 1995) is not appended to this report. All the relevant material in the thesis appears in Ostdiek and Blumen (1995, 1997), which appear above as references 1) and 5).

5. Interactions

a. Presentations

1. Fronts and inertial oscillations. Cyclone Workshop, Pacific Grove, California, December 7, 1995, V. Ostdiek and W. Blumen.

2. American Meteorological Society Conference on Mesoscale Meteorology, Reading, UK, 9–13 September 1996.

    a) Frontogenesis in the presence of inertial oscillations. Talk on September 9.

    b) Session I chair on September 9.

3. American Meteorological Society conference on Boundary Layers and Turbulence, 28 July–1 August 1997, Vancouver, B.C., Canada.

    1) Effects of a dry cold front passage on surface layer turbulence (oral)

    2) Sampling of coherent structures conditioned on bursts of kinetic energy dissipation rate (poster)

4 American Meteorological Society annual conference, 12–16 January 1998, Phoenix, Arizona.

    1) Observations of inertial oscillations in the vicinity of fronts.

    2) Hot-wire anemometer measurements of dissipation rate in surface-layer turbulence.

b. Consultative and advisory function

Planning committee member of the Cooperative Atmosphere-Surface Exchange Study site (CASES), a boundary layer observartional site in south central Kansas

(Reference: Overview and Implementation of CASES, edited by John Pflaum, 1996, 48pp.)

First experiment April–May 1996.

Second experiment planned for October 1999.

6.3 Transitions

MICROFRONTS Data Set

CLASS soundings from the MICROFRONTS field experiment can be retrieved from the World Wide Web at the UCAR Joint Office for Science Support (JOSS) CODIAC data management system:

http://www.joss.ucar.edu/cgi-bin/codiac/ds_proj?MICROFRONTS

The MICROFRONTS hot-wire anemometer data are also maintained by JOSS; however, owing to the prohibitively large size of the data sets, these data cannot be accessed from the CODIAC data server. Instead, the contact person at JOSS for these data is:

Nimal Gamage

UCAR/JOSS

P.O. Box 3000

Boulder, CO 80307

Phone: 303-497-2632

Fax: 303-497-8158

E-mail: gamage@ucar.edu

The NCAR Atmospheric Technology Division (ATD) Surface Systems and Soundings Facility (SSSF) ASTER facility, with its complement of turbulence instrumentation, including sonic anemometers, fast thermometers and hygrometers, was also deployed at the MICROFRONTS field site. The MICROFRONTS ASTER data are also freely available, and can be obtained by contacting NCAR/ATD/SSSF via

Tom Horst

NCAR/ATD/SSSF

P.O. Box 3000

Boulder, CO 80307

Phone: 303-497-8838

Fax: 303-497-8770

E-mail: horst@ncar.ucar.edu

1) MICROFRONTS data are being used by the ARM-CART research community as a part of their data set. This was a two-way interchange: the University of Colorado group (MICROFRONTS) received full access to the ARM-CART (Atmospheric Radiation Measurement-Clouds and Radiation testbed) dataset. The ARM-CART data provides the project with enhanced observations in the form of sonde data and profiler data which are presently being used in MICROFRONTS research. ARM-CART: dje@ornl.gov or ar-

marchive@ornl.gov.

2) The GEWEX (Global Energy Water Cycle Experiment) Continental Scale International Project (GCIP) had an ESOP (Enhanced Seasonal Observing Period). These data have been supplied to the MICROFRONTS research group, and the GCIP obtained the MICROFRONTS data in exchange. GEWEX: gewex@cais.com.

3) The Joint Office for Science Support (JOSS, UCAR) has developed a quality control process for the MICROFRONTS data set. This process, developed by Co-Investigator Nimal Gamage, has been adapted for quality control of all surface data acquired by the GWEX-GCIP project.

4) MICROFRONTS data have been requested and obtained by 47 individuals through the CODIAC data server and UCAR. CODIAC is the central archive for the MICROFRONTS data, and has high visibility in the community being also the data server for part of GCIP. The level of logging does not allow any analysis of the nature of the use of the data or even the actual identity of the person requesting the data. A generic request to acknowledge the program accompanies any data request/service. gamage@ucar.edu.

5) Articles using the MICROFRONTS data set:

Mahrt, L., 1997: Stratified atmospheric boundary layers and breakdown of models. Submitted to the J. of Theor. and Comp. Fluid Dynamics.

Howell, J. and J. Sun, 1997: Surface layer fluxes in a stable boundary layer. Submitted to Bound. Layer Meteorol.

Sun, J., 1997: Use of surface radiation temperature in the bulk formula.

Submitted to Bound. Layer Meteorol.

7. New discoveries, patents, inventions

none

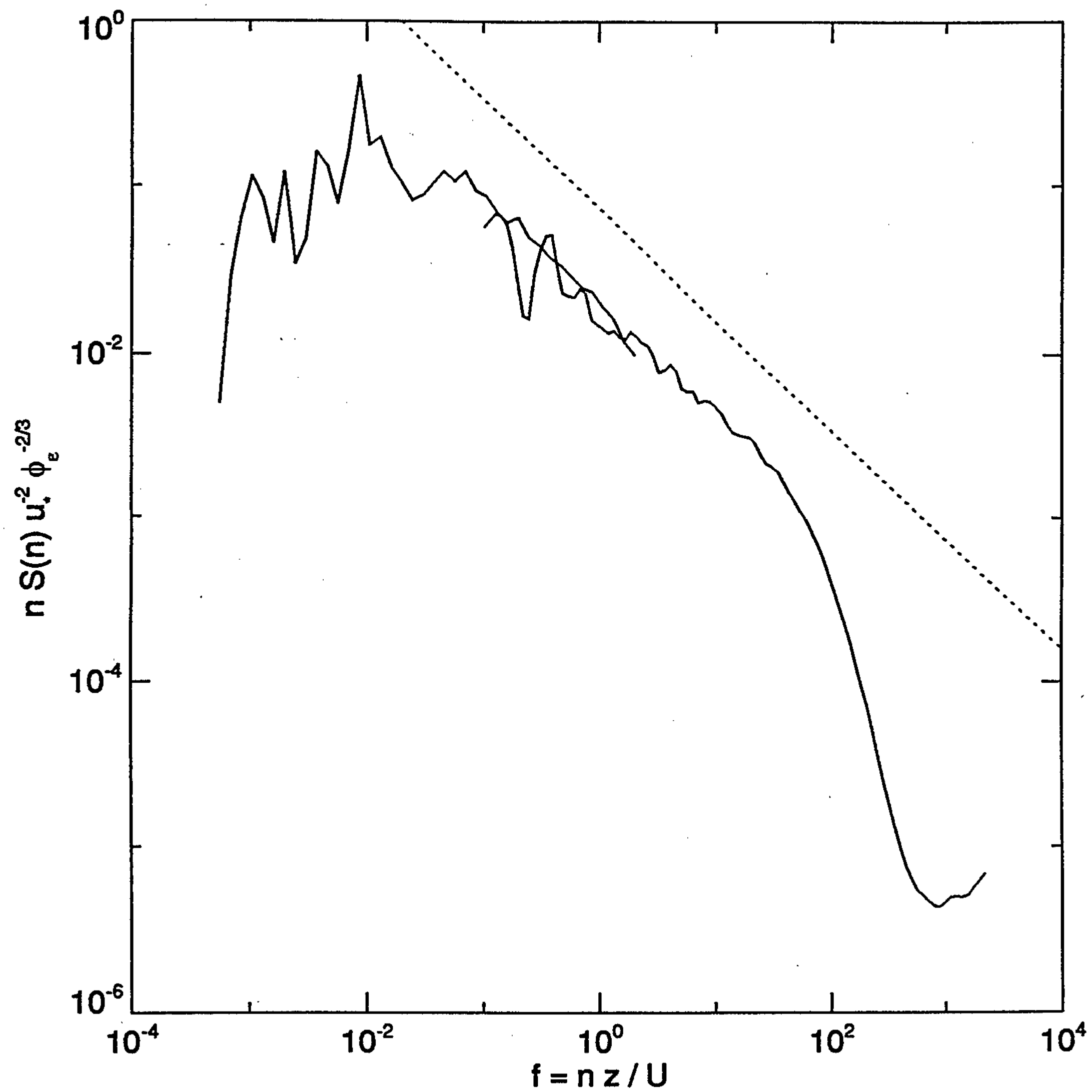

Figure 1. A dimensionless composite energy spectrum computed from sonic and hotwire anemometer data at 3 m. The sonic spectrum, consisting of 40 block-averaged spectral estimates, overlaps the hotwire spectrum, composed of 100 spectral estimates, in the frequency band $0.1 < f < 2$. The dotted line shows a negative two-thirds slope.

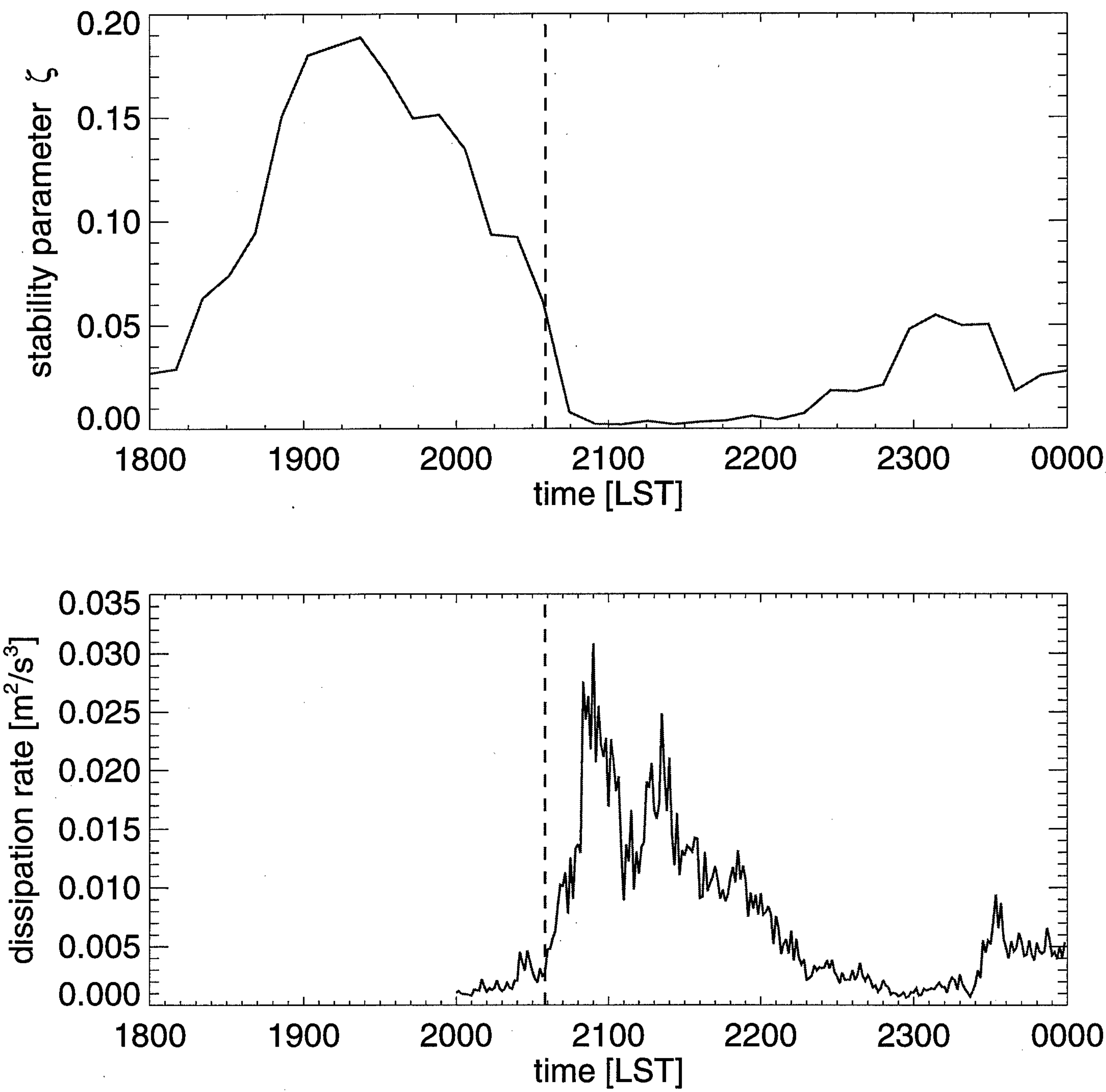

Figure 2. *Top:* A time series of the Monin-Obukhov stability parameter ζ for a six-hour period surrounding the passage of the March 19 cold front. The time of the frontal passage is marked by the vertical dotted blue line. *Bottom:* Time series of dissipation rate ϵ directly calculated from the hot-wire anemometer.

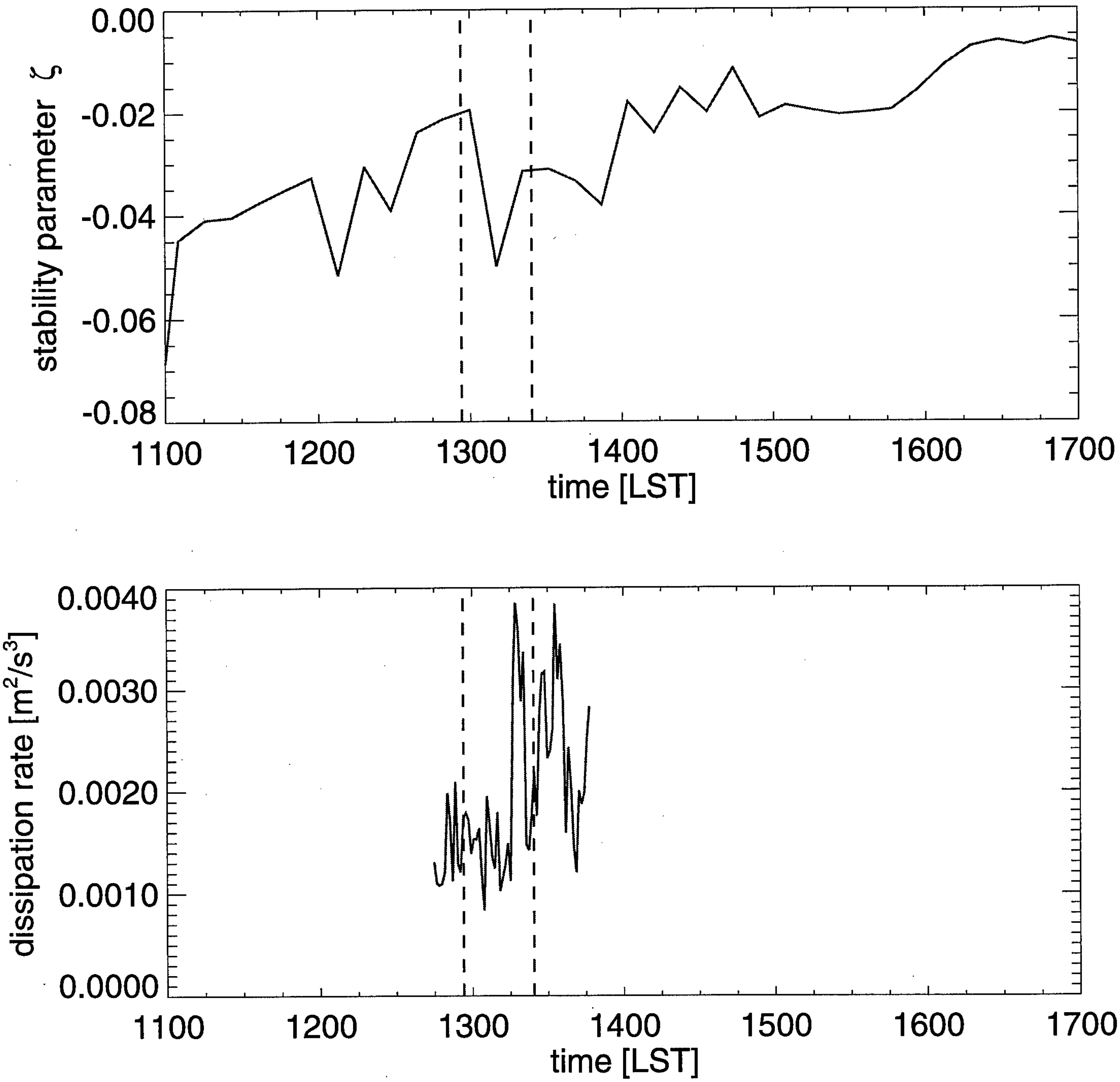

Figure 3. Same as Figure 2, except for the March 26 cold front.

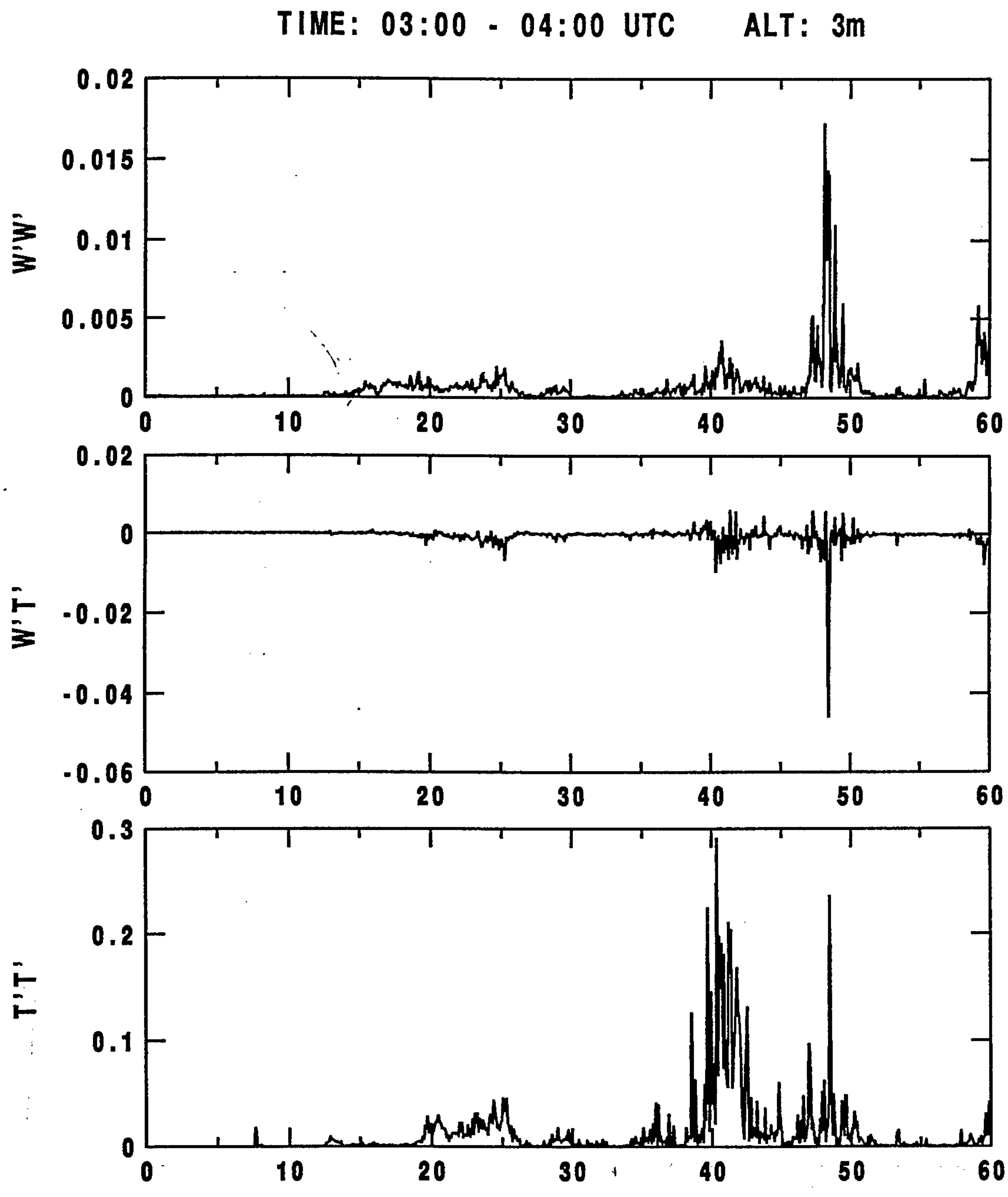

Figure 4. Vertical velocity variance, heat flux and temperature variance (dimensional) based on 10 Hz data at 3m on March 19, 1995 (2100—2200 CST, March 18, 1995).